OPTIMAL POSITION AND PATH PLANNING FOR STOP-AND-GO LASERSCANNING FOR THE ACQUISITION OF 3D BUILDING MODELS

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ABSTRACT:

Terrestrial laser scanning has become more and more popular in recent years. The according planning of the standpoint network is a crucial issue influencing the overhead and the resulting point cloud. Fully static approaches are both cost and time extensive, whereas fully kinematic approaches cannot produce the same data quality. Stop-and-go scanning, which combines the strengths of both strategies, represents a good alternative solution. In the scanning process, the standpoint planning is by now mostly a manual process based on expert knowledge and relying on the surveyor's experience. This paper provides a method based on Mixed Integer Linear Programming (MILP) ensuring an optimal placement of scanner standpoints considering all scanner-related constraints (e.g. incidence angle), a full coverage of the scenery, a sufficient overlap for the subsequent registration and an optimal route planning solving a Traveling Salesperson Problem (TSP). This enables the fully automatic application of autonomous systems for providing a complete model while performing a stop-and-go laser scanning, e.g. with the *Spot* robot from *Boston Dynamics*. Our pre-computed solution, i.e. standpoints and trajectory, has been evaluated surveying a real-world environment using a 360° panoramic laser scanner and successfully compared with a precise LoD2 building model of the underlying scene. The performed ICP-based registration issued from our fully automatic pipeline turns out to be a very good and safe alternative of the otherwise laborious target-based registration.

1. INTRODUCTION

In recent years, terrestrial laser scanning (TLS) has been used more and more frequently to perform surveying tasks and for the mapping of 3D environments. The rapid evolution of sensor technology allowed for a significant growth of both efficiency and attractiveness of TLS in various fields of application ranging from engineering geodesy through architecture to monitoring of construction sites and the generation of as-built models of existing buildings as well. In this context, two prominent surveying approaches are applied: static and kinematic laser scanning. Basically, static laser scanning offers a high quality of the resulting 3D point cloud but often suffers from a low level of efficiency due to the high measurement overhead. Meanwhile, kinematic laser scanning usually relies on the use of an Inertial Measurement Unit (IMU) and a GNSS receiver. Thus, it is possible to continuously capture georeferenced point clouds. This allows for a higher measurement efficiency; however, the quality of the acquired point cloud is in general suffering from the uncertainty of the IMU and GNSS unit. This can be intensified by influencing factors such as existing bumps in the road surface and by limiting GNSS visibility close to buildings. Other factors such as the velocity of the mobile platform of kinematic systems can also have a negative impact limiting the resolution and the possibilities to affect this compared to static systems. For more details on both paradigms, the interested reader is referred to the survey conducted by Lin et al. (2013).

In order to exploit the strengths and avoid the drawbacks of both surveying strategies, stop-and-go laser scanning is therefore an appropriate alternative. The latter represents a compromise between efficiency and measurement accuracy. In this context, terrestrial laser scanner sensors are mounted on mobile platforms allowing for a mixture between a static and a kinematic data acquisition procedure. Following this paradigm, the *Boston Dynamic Spot* has been augmented by the *RTC360* scanner from *Leica*[1] in order to enable an agile, and mobile fully automated workflow for a 3D scanning of environments. In this way, the walking robot can easily navigate programmed scanning paths. Such pre-defined paths and in particular the positioning of the standpoints are mostly determined ad-hoc based on expert knowledge. In this paper, we suggest and implement a two-staged method for an optimal stop-and-go laser scanning approach, which in a first step (1) yields a minimum number of scanner standpoints while (a) considering laser scanner constraints, e.g. incidence angle, (b) ensuring a satisfactory overlap between the laser scans for a subsequent registration, guaranteeing (c) a full coverage of the considered scene and in a second step provides (2) an optimal navigation path to follow for (3) the 3D surveying of an outdoor site. For both sub-tasks, i.e. optimal standpoints and optimal route, we formulated a (Mixed) Integer Linear Program ((M)ILP). The first MILP is a flow-based formulation whereas the second part is an ILP solving the well-known Travelling Salesperson Problem (TSP) (Dantzig et al., 1954; Cormen et al., 2009). In this manner, our method opens up new possibilities for a fast and efficient, autonomous capturing of 3D outdoor scenes. Even in a non-autonomous fashion, this approach can significantly reduce the surveying time and thus the cost of measurement campaigns based on the optimally planned standpoint locations and the pre-computed work-

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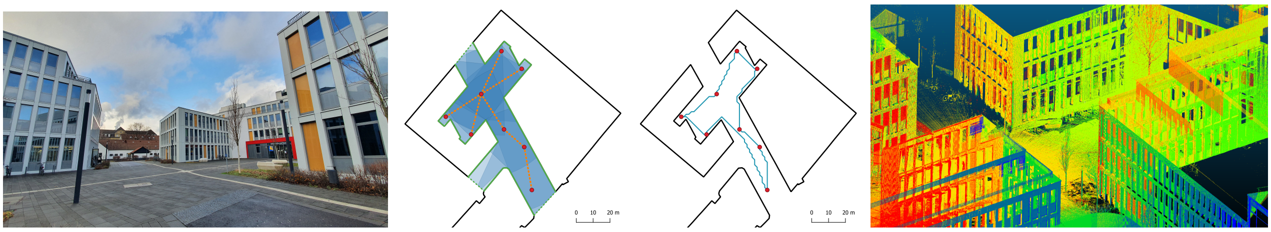

(a) (b) (c) (d)

Figure 1. Illustration of the real-world application of our pipeline on the building complex as shown in (a). Given the boundaries of the scene marked by the (dotted) green lines, we compute optimal sensor positionsr (red) based on sensor constraints while simultaneously guaranteeing a full coverage and a satisfactory overlap (depicted by the differently intense colors) for the subsequent registration process (b). This is followed up by the calculation of the optimal route (c) resulting in a point cloud as shown in (d).

flow scheduling.

When tackling the stop-and-go laser scanning, two task have to be solved: (1) The optimal selection of scanner positions to obtain a full coverage of all structures to be scanned and (2) finding an optimal route between these standpoints. The first part is a variant of the well-known Art Gallery Problem (AGP) – the task to find the minimum number of guards to supervise a whole art gallery. This problem is proven to be NP-hard (Lee and Lin, 1986). Although several solutions for different variants of the AGP exist (Kröller et al., 2013; de Rezende et al., 2016), these are often representing approaches from theoretical computational geometry and are not aligned with the peculiarities of laser scanning including crucial parameters such as the measurement range and the minimum incidence angle, which highly impact the quality of the resulting point clouds (Soudarissanane et al., 2011). In the context of laser scanning, the AGP problem corresponds to the view planning problem (VPP), which is in practice mostly solved by leveraging expert knowledge of the user in a manual fashion. Thus, solutions considering the above-mentioned factors and the scanning geometry seem to be worthwhile (Soudarissanane and Lindenbergh, 2012; Jia and Lichti, 2019).

Our approach builds upon a recent publication by Dehbi et al. (2021), which not only considers the laser scanner related parameters, but moreover ensures further connectivity constraints: These constraints aim for a sufficient overlap between the particular scans in order to ensure a satisfactory result when registering the individual scans, e.g. with an Iterative Closest Point algorithm (ICP) Besl and McKay (1992). As yet, this approach focuses on indoor environments and addresses only optimal scan planning for static TLS. In order to enable a stop-and-go strategy, we adapt and expand this method allowing not only for an autonomous mapping but also ensuring both optimal standpoints and optimal navigation as well. This can be carried out by solving the TSP, which like the AGP is also proven to be NP-hard (Cormen et al., 2009). For this reason, we follow a step-wise approach consisting in solving both problems separately and in an optimal fashion. Figure 1 depicts the real-world application of our approach, performed on the buildings shown in 1(a). In our experiments, we used a 360° panoramic laser scanner to conduct a survey of the complete scene. The result of the first part of the algorithm, i.e. the optimal scanner positions is depicted in 1(b), the differently intense colored areas show the overlap between the particular scans. In 1(c) the result of the second step, i.e. the calculation of an optimal route, is visualized. The acquired point cloud of the underlying scene is shown in 1(d).

The remainder of this paper is organized as follows: Section 2 yields an overview over the relevant related research, followed by Section 3, in which the applied methodology is explained, regarding the search of the optimal scanner positions (Section 3.1) and the path connecting them (Section 3.2). The outcomes of the conducted experiments are presented and discussed in Section 4. Section 5 summarises the paper and gives an outlook in open research questions.

2. RELATED WORK

Standpoint planning As mentioned, the problem we aim to solve is closely related to the well-studied Art Gallery Problem (AGP) In this context, the goal is to place a certain amount of guards in such a way that a whole art gallery is monitored with the fewest number of guards possible. Therefore, the gallery is represented by a Polygon P with a number of n vertices.

The proposed method builds upon a formulated (Mixed) Integer Linear Program (MILP). In a related context, Kröller et al. (2012) combined Integer Linear Programming (ILP) and difference of convex functions for optimally solving the AGP and providing lower and upper bounds on the minimum number of guards. Couto et al. (2011) addressed AGP as a Set Cover Problem by also solving an ILP.

The above mentioned approaches urge for the development of efficient algorithms in the field of theoretical computational geometry. Considering the aim of this paper, which is laser scanning of 3D environments, these approaches show some shortcomings. On the one hand, most of them restrict the placement of the guards on the boundary of the gallery at hand. In our context, there should be no restrictions on the placement of the sensors. Simultaneously, the positions should be as far as necessary from walls and obstacles in order to suffice the sensor restrictions and follow the manufacturer's recommendations (Soudarissanane et al., 2011). Soudarissanane and Lindenbergh (2012) proposed a greedy approach providing laser scanner standpoints considering range and angle constraints: For this purpose, the walls are divided into subsegments. Given candidates for scanner positions, the visibility of the segments is considered by iteratively choosing the candidate covering the highest number of unobserved wall segments so far. This greedy approach is performed until every wall segment is covered. Likewise, González-Banos (2001) suggested a technique for the determination of sensor positions based on a random sampling strategy. Wujanz et al. (2016) presented a method addressing the trade-off between economical aspects and achievable precision. In the context of heritage recording, Ahn and Wohn (2016) considered beside the scanner related constraints the overlap between laser scans from different standpoints. This approach is, however, not fully automatic since a user intervention is needed to select sensor positions based on standpoint proposals. Díaz-Vilariño et al. (2019) focus on the recording of archaeological sites introducing a triangulation approach for generating standpoint candidates to reduce computational time for large areas.

All approaches mentioned above do not take care of the subsequent registration step of the scans stemming from different standpoints. Jia and Lichti (2019) proposed a hierarchical strategy to greedily minimize the number of laser scanner positions. In contrast to our method, they followed a target minimization method. However, a target-based registration which requires a pre-setup of the targets is even time consuming compared to a software-based procedure which guarantees a successful registration as we propose. Dehbi et al. (2021) proposed an approach, which our method draws upon, where beyond the sensor related constraints the connectivity of the resulting optimal standpoint network is ensured based on a flow problem formulated as an MILP. This approach has been designed for surveying indoor models in a static fashion. This motivates its adaptation for the automatic generation of standpoint network plans in a stop-and-go manner for the acquisition of 3D models of outdoor sites.

Our method aims at efficiently registering the particular scans and ensuring their co-registration. In the literature dealing with the registration of point clouds, it is commonly differentiated between coarse and fine registration methods: Coarse registration methods usually rely on target or tie points which are present in different scans. In this context, feature-based coarse registration using points, lines or surfaces as invariant objects are, however, widely used. Brenner et al. (2008), for instance, utilized primitives such as planar patches for a coarse registration. Theiler and Schindler (2012) used the intersections of natural planar surfaces to generate virtual tie points for the automatic registration of TLS point clouds. Prominent methods for fine registrations are Iterative Closest Point (ICP) (Besl and McKay, 1992) and RANdom SAmple Consensus (RANSAC) (Fishler, 1981). Herewith, a maximum overlap between the different point clouds is targeted. The interested reader is referred to Cheng et al. (2018) where a review of state of the art registration techniques has been performed.

Stop & go laserscanning and routing In the context of a kinematic laser scanning, the problem is related to the well-known Next Best View problem (NBV), where the scans conducted so far are considered to find the next position for the laser scanner. Quintana et al. (2016) proposed a scanning process in which potential structural elements of building interiors are learned as a new scan updating a non a-priori hypothesized workspace. Our method suggests optimal scanning plans for a stop-and-go approach. Lin et al. (2013) analyzed advantages and disadvantages of this strategy compared to fully-static and fully-kinematic terrestrial laser scanning and emphasized the importance of sensor manipulation during the mapping phase. While static laser scanning is time-consuming and thus expensive, the quality of the resulting point cloud is lower in a kinematic scanning process. This is mainly attributed to the uncertainty resulting from the referencing of the points by an inertial measurement unit (IMU) and GNSS. Further, the distribution of the points on the measurement object is very difficult to control, e.g. with regard to the resulting resolution. That is why they recommend the use of stop-and-go laser scanning, which combines the advantages of both variants and reduces the disadvantages. Likewise, Chow et al. (2014) introduced following this paradigm the so-called *Scannect* which aims for a 3D mapping of indoor environments, using a combination of LiDAR, *Microsoft Kinect* sensors and an IMU.

Most of the mentioned approaches emphasize finding sensor positions, but no routes are suggested. Bolourian and Hammad (2020) solve a Travelling Salesperson Problem (TSP) to control and monitor bridges for possible damages using an unmanned aerial vehicle (UAV) equipped with a LiDAR sensor. This approach guides the UAV to visit positions calculated considering different levels of criticality by calculating the visibility. Predefined damage positions with a higher level of criticality obtain a larger overlap between individual shots accordingly. An overview over different variants of the TSP in the context of unmanned aerial vehicles can be found in Khoufi et al. (2019). Similar to the method presented in this paper, Kuželka and Surový (2021) used Integer Programming to solve the TSP for finding the optimal positions of cameras in order to reconstruct a forest environment using Structure from Motion.

In the context of stop & go laserscanning, Frías et al. (2019) focus on the monitoring of the construction progress based on an underlying Building Information Model (BIM). They carry out a visibility analysis by, however, only considering the maximum range as a scanner related constraint. Surveying with a short range allows them to neglect the incidence angle. Furthermore, they do not address overlapping and, hence, do not guarantee a successful subsequent registration. They, however, deal with the connectivity by allowing the placement of standpoints in door areas, which does not turn out to be always the optimal choice as revealed by comparing an expert network design with the method of Dehbi et al. (2021). The routing process itself is based on a probabilistic ant colony optimization algorithm dedicated for surveying an indoor environment. Although they tackle a similar task as ours, however, there are significant differences: First, we aim for an optimal route suggestion rather than a heuristically determined navigation path. To this end, our method provides an optimal routing solving the well-known Travelling Salesperson Problem (TSP) (Cormen et al., 2009), using an ILP formulation (Dantzig et al., 1954) based on the optimally suggested scanner positions from Dehbi et al. (2021). Furthermore, our goal is to provide a framework which can be used in an outdoor environment and is not restricted for indoor applications. Moreover, the algorithm used here for providing the optimal sensor positions not only considers the visibility, but guarantees that every part of the target objects can be seen from at least one standpoint. Additionally, the registration process is considered in the optimization process ensuring that every standpoint can be registered to its neighbored points, for instance by the use of the Iterative Closest Point algorithm (ICP), by guaranteeing a sufficient overlap between the scans and therefore a sufficient and satisfactory registration result.

3. METHODOLOGY

3.1 Optimal selection of scanner positions

As mentioned, the first step towards the planing of navigation paths for a stop-and-go platform is the determination of the sensor locations where the moving vehicle has to stop. In our paper, we are rather interested in an optimal network of standpoints aiming at a minimum number of scanner positions. For this task, our approach draws upon ideas from the publication by Dehbi et al. (2021), in which such an optimal network has

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been automatically determined to survey 3D scenes. Basically, this method has been demonstrated for scan planning of interior scenes for the acquisition of 3D indoor models based on an according floor plan with occurring obstacles. Nevertheless, we adapted and extended this method to further address outdoor sites. For the sake of clarity and readability, we introduce the main ideas from Dehbi et al. (2021) in the following.

Compared to the indoor context, where the scene was bounded by the outline of the underlying building, the outdoor environment to capture could, however, contain several polygons. The latter represent the geometry of the scene at hand, e.g. buildings and obstacles, limited by a boundary polygon B. Moreover, areas where the positioning of a scanner instrument is not possible can be modeled as restricted areas by a set A of polygons $A_1, \ldots, A_m$. In this context, given a set P of polygons $P_1, \ldots, P_n$ the goal is to minimize the number of laser scanner positions from a set S needed to retrieve a complete measurement of both walls and floor. For this, completeness is guaranteed by demanding a full coverage of all walls of this building. The actually 3D problem is safely reduced to a 2D search space. The points to be covered, e.g. wall points, are represented by a continuous set $\mathcal{R} \subseteq \mathcal{P}$. These points are monitored by a discrete set CP of candidate points lying on an instantiated grid on $B \setminus (P \cup A)$. The set $\mathcal{R}$ is carefully discretized into a finite set R whose coverage implies the full coverage of $\mathcal{R}$ which will be explained later on. In this manner, the full coverage of all polygons of P corresponds to finding a set $S \subseteq CP$ of positions $s \in S$ which fully covers R. This in turn means that $\mathcal{R} \subseteq \cup_{s \in S} \mathcal{V}(s)$, where $\mathcal{V}(p)$ denotes the visibility polygon including all points in P which are visible from a given point p. An example of the visibility polygon of such a point is depicted in Figure 2. In order to consider obstacles and determine the visible parts accordingly, the efficient algorithm of Asano (1985) has been applied. The determination of visibility polygons takes further the specific constraints related to laser scanning such as minimal and maximal range and incidence angle of the laser beam into account. The problem at hand corresponds to a Set Cover Problem which has been formulated as an Integer Linear Program (ILP) with the variables $x_p \in \{0, 1\} \quad \forall \quad p \in P$, which can be interpreted as follows:

$$x_p = \begin{cases} 1 & , \text{ if } p \text{ is selected as a station point} \\ 0 & , \text{ otherwise} \end{cases} \tag{1}$$

The ILP is subject to the following objective function:

$$\text{Minimize} \quad \sum_{p \in P} x_p, \tag{2}$$

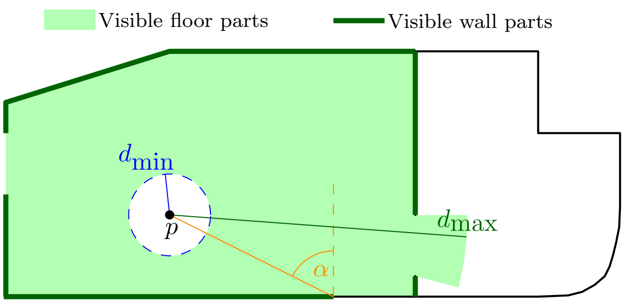

Figure 2. Visibility polygon from a position p. Minimal and maximal range, incidence angle as well as obstacles are considered, adapted from Dehbi et al. (2021).

while considering the constraint

$$\sum_{p \in \{q \in P | r \in \mathcal{V}(q)\}} x_p \geq 1 \quad \forall r \in R \tag{3}$$

Constraint 3 ensures that each point $r \in R$ has to be observed by at least one station point. If a particular point r is not observable from any standpoint candidate the according areas are not considered correspondingly.

To ensure a full coverage of the set $\mathcal{R}$ despite the discretization R, a set C of *critical points* is calculated. For a given standpoint position p, such critical points are partitioning a given wall into a visible and non-visible part incorporating the maximum and minimum range of the sensor and the incidence angle as well as other obstacles, e.g. other walls, limiting the visibility. In this manner, the wall is discretized into a sequence of segments bounded by consecutive critical points c_i and c_{i+1}. A full coverage is then guaranteed if Constraint 3 is instantiated for one representative point for each segment (e.g. the middle).

A further important aspect to address is ensuring a sufficient overlap between the visible parts from neighbored scanner positions. This has a high impact on the quality of the subsequent registration, e.g. using ICP. To this end, a graph $G = (V, E)$ is instantiated where the vertices V correspond to the standpoint candidates. In this context an edge $e = \{u, v\}$ exists if two vertices u and v share at least a minimum length L_{min} of the overlap between $(V(u) \cap \partial\mathcal{P})$ and $(V(v) \cap \partial\mathcal{P})$, with $\partial\mathcal{P}$ denoting the boundary of $\mathcal{P}$.

In order to ensure not only a sufficient bilateral overlap between neighbored stations but also guarantee a global connectivity of the station network, the ILP is extended by additional integer and continuous variables and therefore becoming a Mixed Integer Linear Program (MILP). The task is then addressed as a flow problem (Shirabe, 2004) on a directed graph $G' = (V, E')$ incorporating opposite directed edges (u, v) and (v, u) for each edge $e = \{u, v\} \in E$ from the previous graph G. The flow can be seen as a unit which has to be transported from a *source* to a *sink* in the graph G'. Ensuring that this unit can reach every node from any given station point, corresponds to guaranteeing an overall connectivity of the underlying network. For the mathematical formulation of the connectivity constraints, the interested reader is referred to Dehbi et al. (2021).

3.2 Optimal path planing for stop-and-go scanning

The resulting network of optimal scan positions from the last section paves the way towards an automatic stop-and-go laser-scanning process. For this aim, the next step consists of applying a path finding algorithm. In this context, the focus is on finding the shortest possible loopy route that connects all points of interest. This corresponds to the well-known Traveling Salesperson Problem (TSP) (Cormen et al., 2009). Since we are further interested in optimal solutions rather than heuristically determined routes, we formulated the TSP as an Integer Linear Program (ILP) using the model of Dantzig et al. (1954). Beyond seeking optimality, addressing both NP-hard sub-tasks, i.e., AGP and TSP, of our two-staged strategy using MILP and ILP is paving the way towards an integrated method dealing with both steps simultaneously in future research. In our context, each of the optimally pre-determined m scanner positions $v \in V$ has to be visited exactly once before returning to the starting standpoint. The aim hereby is to minimize the total distance w_{tot}, that must be traveled to visit every standpoint v_i with $i = \{1, ...m\}$ which corresponds to the shortest possible route.

The search space of possible routes is instantiated based on a complete directed weighted graph $\hat{G} = (V, \hat{E})$, which is also exemplarily depicted in Figure 3. Herewith, each vertex $v \in V$, depicted in orange, corresponds to a selected standpoint from the previous optimization problem. In this context, an edge $\hat{e} = (u, v)$, depicted in red, is introduced for each pair of distinct vertices u and v. An edge weight $w_{uv} \in \mathbb{R}^+$ indicates the distance to be travelled between the two according positions of u and v. This is a crucial parameter which will be discussed in more details later on. The graph $\hat{G}$ represents the basis for the formulation of the ILP for solving the TSP. To this end, a variable $x_{uv} \in \{0, 1\}$ is introduced for each edge $e = (u, v) \in \hat{E}$ which can be interpreted as follows:

$$x_{uv} = \begin{cases} 1 & , \ \text{if positions u and v are connected} \\ 0 & , \ \text{otherwise}\,. \end{cases} \tag{4}$$

The task now is to minimize the following objective function:

$$\text{minimize} \sum_{u,v \in V} w_{uv} \cdot x_{\mathrm{uv}}, \tag{5}$$

leading to the targeted shortest route w_{tot}. Since the graph $\hat{G}$ is directed, a symmetry constraint is introduced enabling to set arbitrary directions between two vertices u and v:

$$x_{\mathrm{uv}} = x_{\mathrm{vu}} \ \forall \, u, v \in V. \tag{6}$$

This model allows for choosing an arbitrary direction to follow. For this reason, the in-degree and the out-degree of each vertex must be exactly 2:

$$\sum_{v \in V, u \neq v} x_{\mathrm{uv}} = 2 \ \forall \ u \in V. \tag{7}$$

The resulting routing graph should be a connected graph in order to avoid and eliminate unintentionally isolated subtours. This means that the resulting path includes all the input vertices. In other words, each subtour containing a set of vertices $V' \subseteq V$ must be connected by at least two edges with the remaining vertices:

$$\sum_{u \in V'} \sum_{v \in V', u \neq v} x_{\mathrm{uv}} \leq |V| - 1 \ \forall \ V' \subseteq V \tag{8}$$

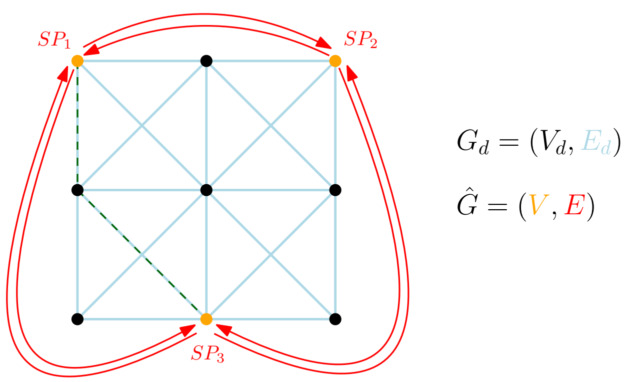

Figure 3. The underlying graphs: The weighted complete graph $\hat{G}$ consisting of optimally selected standpoints (orange vertices) is the basis for the TSP. The weights are induced building upon the graph G_d on an octilinear grid. The weight w of the edge connecting SP_1 and SP_3 corresponds to the geometric distance on the octilinear grid (green dashed path).

The weight w_{uv} of each edge $\hat{e} = (u, v)$ is computed on an octilinear grid (blue color) as depicted in blue in Figure 3. In this manner, we allow for octilinearly directed edges based on the grid of possible standpoint candidates CP (black points) from the previous section represented by a graph $G_d = (V_d, E_d)$. Such a discretization offers the possibility to move around walls, corners and other existing obstacles. Since the candidate vertices V_d have been instantiated far away from walls and obstacles, our procedure guarantees a navigability through the vertices of the graph G_d. This is the basis for performing a classical shortest path search for the determination of each weight w_{uv} based on the A*-algorithm (Hart et al., 1968).

Since we assumed a TSP the result is a round trip. However, a loop closure is not necessary. In this context, either the longest subsection of the route can be omitted or the starting point can be arbitrarily chosen omitting the loop closure.

4. EXPERIMENTS

In order to demonstrate the feasibility of our proposed method and the quality of the resulting 3D point clouds, we performed the whole pipeline on a real-world example using an *Imager 5016* panoramic laser scanner from *Zoller&Fröhlich*. The scene is a part of the campus of the University of Bonn and is characterised by several protrusions and porticoes. Therefore, an ad-hoc placement of the scanner instrument is challenging, even for an expert, when a complete coverage is targeted. The whole scene has an area of 2.800 m^2 approximately.

Planning and results As mentioned, our method expects a 2D polygon of the underlying environment as an input. In order to allow for an automatic stop-and-go strategy, we make use of a georeferenced polygon extracted from *OpenStreetMap* (OSM). The following scanner related parameters have been used in our experiments: the minimum incidence angle is 70°, the minimum range $d_{\min}$ and maximum range $d_{\max}$ are 1m and 50m respectively. The latter value is smaller than the manufacturer's recommendations. This choice is, however, legitimate avoiding higher uncertainties with higher distances. For the grid step length, we choose a value of 1.5m. As mentioned, the grid allows for the instantiation of standpoint candidates, disregarding a-priori known obstacle regions. In order to guarantee sufficient space to place the measurement instruments, we buffered regions in wall and obstacle proximity. The resulting grid (black dots) can be seen in Figure 4. Concerning the registration parameters, the parameter $L_{\min}$, which denotes the minimal overlap between two wall parts observed from two consecutive standpoints, has been set to 50m. This represents a suitable value to ensure a safe co-registration of the adjacent scans using an ICP later on.

In a first step, our method calculates an optimal standpoint network of the scanner positions based on the above mentioned settings by solving the MILP from Section 3. For the scene at hand, the resulting network consists of 8 standpoints (red dots) as can be also seen in Figure 4. It can be stated that four scanner positions are placed in the middle of the scene, i.e. between the northeastern and southwestern buildings. The remaining four

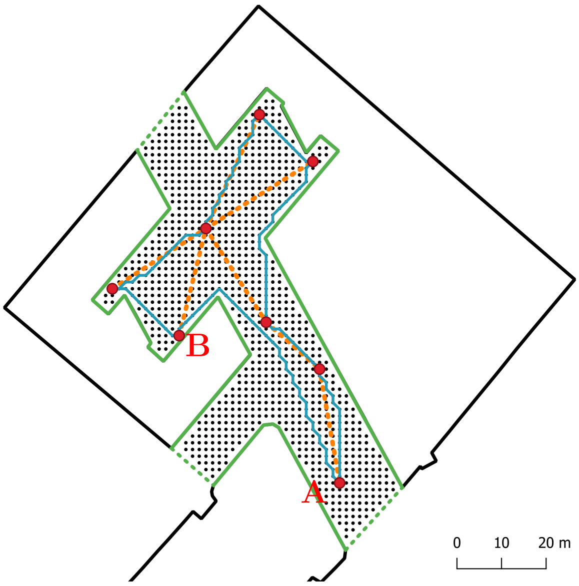

Figure 4. The Standpoints (red) calculated based on the candidate points lying on a grid (black dots), the connectivity graph for registration (orange) and the optimal route (blue).

standpoints are located near the corners of the semi-open courtyard. This is due to the fact that the scanner position in the middle is not able to capture the whole porticoes of the two buildings which can be shown in Figure 5. Obviously, the upper region highlighted by a bigger circle is not covered by this standpoint. The wall segments colored in red indicate that the constraint enforcing the minimum incidence angle is violated there. A closer look even reveals that another smaller wall segment on the bottom of the same figure remains also unobserved (smaller circle). The according point cloud is subsequently incomplete as can be shown in the upper left part of the figure. For this reason, additional standpoints were needed to ensure a full coverage of the whole environment. The second step is to pre-compute the navigation route for the stop-and-go scanning procedure by solving the TSP. The resulting round trip is further depicted in Figure 4 (blue color). It should be noted that the route connects the standpoints A and B even if they do not share a sufficient overlap for the registration which is confirmed

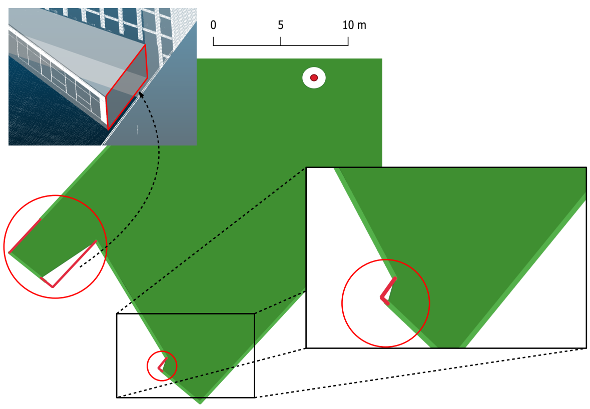

Figure 5. Visibility polygon (green) of the scanner (red point) positioned in the upper right corner of an excerpt of the scene. Red wall elements cannot be observed due to the violation of the incidence angle constraint. The point cloud stemming from this standpoint is accordingly incomplete (upper left).

by the connectivity graph (orange). The co-registration of these two standpoints is, however, guaranteed by the a-priori ensured connectivity. The calculated route represents the prerequisite for the subsequent survey step. The latter has been carried out with the *Imager 5016* in a stop-and-go fashion.

In order to acquire a georeferenced 3D point cloud, two additional standpoints, which are not part of the determined optimal network, have been used. This allows for a quality assessment of the point cloud compared to other georeferenced models, such as cadastral data. In this context, we visualized our final point cloud, resulting from the ICP based registration of individual scans at the different standpoints (Figure 7, white color). The residuals resulting from the ICP range from 3 to 6mm for the respective standpoints. In the same scene, we visualized also a georeferenced precise building model of the scenery stemming from authoritative cadastral data. The building models are in the Level-of-Detail 2 (LoD2) according to the standardized CityGML format (Gröger et al., 2012). These models are characterised by an accuracy of few centimeters on the ground. It can be stated that all facades of the buildings have been fully captured. Missing regions correspond to reflective objects such as windows and glass fronts as can be seen in the RGB view of the scene (cf. Figure 1(a)).

Comparison with an expert's solution Furthermore, we compared the scanner positions computed by our pipeline with a solution designed by an expert for surveying the whole scenery (cf. Figure 6). This designed network consists of one standpoint less than our suggested solution. Nevertheless, the expert's proposed standpoints do not guarantee a full coverage of all wall parts of the buildings considering the scanner constraints, e.g. the minimal incidence angle. The otherwise missing parts of the walls are depicted in red. It should be noted that this solution was designed for a target-based registration process, which is much more time consuming compared to an ICP-based registration, but needs smaller areas of overlap between the scans. It is often carried out to ensure a successful registration.

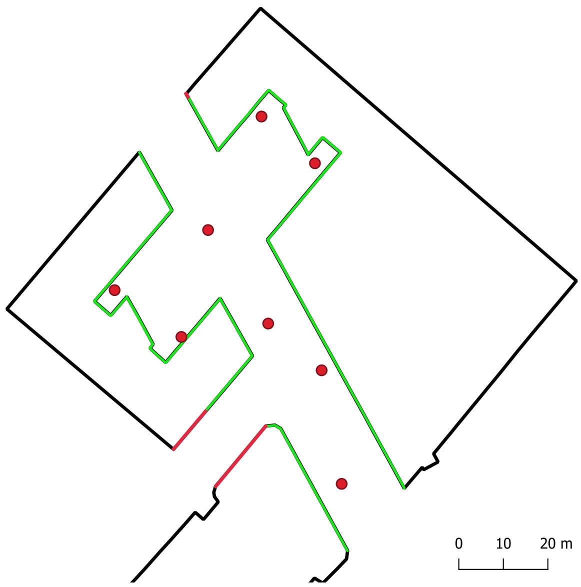

Figure 6. Scanner positions chosen by an expert and the corresponding visible (green) and not visible parts (red) of the buildings considering the scanner related constraints.

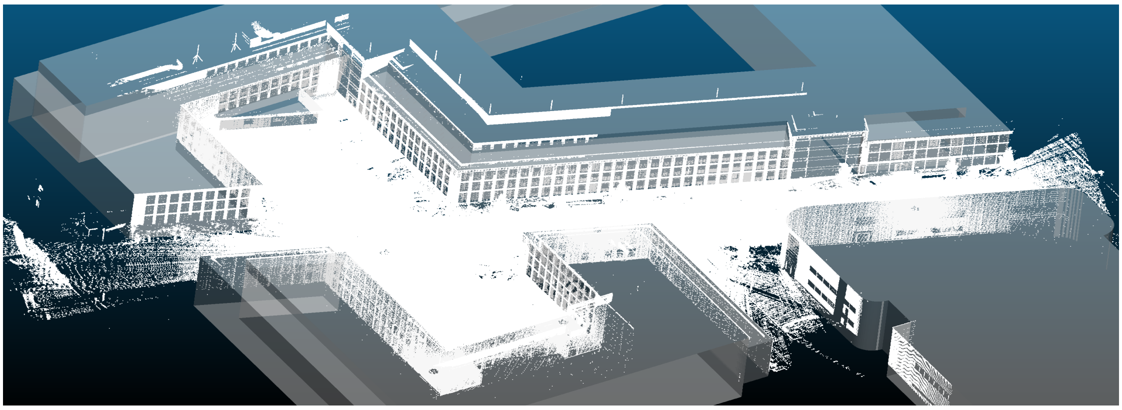

Figure 7. Captured scene of the Poppelsdorf campus of the University of Bonn. Acquired point cloud based on our planned standpoint network and navigation path matched with a precise authoritative LoD2 model of the surrounding buildings.

Furthermore, we conducted a Cloud2Cloud (C2C) comparison of both point clouds, i.e. ours and the experts, after omitting shrubs and other vegetation. Figure 8 presents on the left a histogram of the absolute distances showing that the majority of the points has a distance of 2cm or less. Additionally, on the right side the distances between the two point clouds in the scenery are depicted. It can be observed that bigger differences can be found at the bottom-right part of the scenery between the buildings, where the expert solution did not fulfill the full coverage requirements of our approach (cf. Figure 6).

To sum up, our approach suggests one standpoint more, but meanwhile guarantees a full coverage, a minimum incident angle of the scans and at the same time a the necessary between individual scans. Therefore it avoids the need for a much more costly target-based registration. Our method promising an automatic network design respecting sensor-related restrictions, providing a full coverage of the underlying scene and leading to a successful software-based registration, e.g. using ICP, turns out to be a very good motivation to renounce the otherwise laborious target-based registration.

5. CONCLUSION

This paper presented a novel approach for the optimal and automatic design of sensor standpoints and navigation path for stop-and-go laser scanning of outdoor building scenes. In a first step, the minimum sensor positions needed to obtain a full coverage of all buildings is performed solving an Art Gallery Problem (AGP) formulated as a Mixed Integer Linear Programming (MILP) considering sensor-related constraints, e.g. incidence angle and measurement range, while simultaneously ensuring a sufficient overlap between subsequent scans for a successful registration. In a second step, an Integer Linear Programming (ILP) formulation of the Traveling Salesperson Problem (TSP) is used to acquire an optimal route building upon the optimally determined standpoints for a stop-and-go scanning procedure.

The whole proposed pipeline has been successfully applied and demonstrated on a large real-world outdoor scenery. The resulting successfully registered point cloud has been compared to a precise LoD2 building model of the underlying environment ensuring a full coverage of all building parts in contrast to a sensor network suggested by an expert. Our method promising an automatic network design respecting sensor-related restrictions, providing a full coverage of the underlying scene and leading to a successful software-based fine registration, e.g. using ICP, turns out to be a very good motivation to renounce the otherwise laborious target-based coarse registration. The MILP and ILP formulation of both AGP and TSP is a good basis for their integration which will be addressed in future research.

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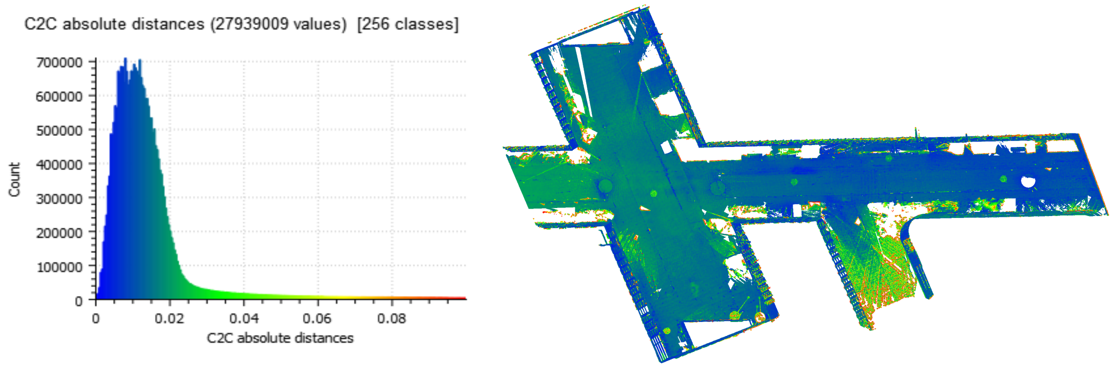

Figure 8. Residuals from the *Cloud2Cloud* comparison of the expert's point cloud and ours: Histogram (left), point cloud (right).

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